

# The Performance of Ultrafine Palm Oil Fuel Ash in Suppressing the Alkali Silica Reaction in Mortar Bar

Hidayati Asrah, Abdul K. Mirasa, Md. A. Mannan

**Abstract**— This study evaluates the effect of ultrafine palm oil fuel ash (POFA) on the alkali silica reaction (ASR) of mortar. To study the effectiveness of ultrafine POFA in suppressing the ASR, four different sizes of POFA were used in this study: the unground (UG), medium (MP), fine (FP), and ultrafine size (UF). Characterization of POFA was done to investigate their particle size, fineness, specific gravity, chemical composition, loss on ignition (LOI), and morphology. Initially, the pessimum effect of the sandstone aggregate was determined by blending 5, 15, 50, 75, and 100% of sandstone aggregates with the granite. POFA was then introduced as cement replacement at 0 - 40% by weight of binder. To investigate the effect of ultrafine POFA on ASR, ASTM C1260 and ASTM C1567 were adopted. The strength activity index was also determined to study the pozzolanic effect of the ultrafine POFA. Results show that the ultrafine POFA significantly increase the pozzolanic reactivity of mortar. At 14-days of testing, ultrafine POFA shows higher resistance against the alkali silica reaction (ASR) attack compared to coarser POFA. Higher level of replacement is required for coarser POFA to resist ASR attack in the mortar bar.

**Index Terms**— Alkali Silica Reaction, Palm Oil Fuel Ash, Reactive aggregate, Ultrafine.

## I. INTRODUCTION

As the second largest palm oil producer in the world, Malaysia has generated million tonnes of palm oil wastes each year. Combustion of palm oil shell and fiber has produced another secondary palm oil waste known as palm oil fuel ash (POFA). With no commercial value, these ashes were dumped near the plantation area [1] and caused air, water and land pollution [2]. Many efforts have been done to use POFA in concrete; however, the coarser size of POFA has led to a decrease in the strength of concrete [3]. This has limited the use of POFA in concrete construction. Later, it was found that grinding process can improve the quality of POFA. The amount of cement replacement increased up to 30% with improvement on the strength and durability of concrete as compared to conventional concrete [4]. These encouraging results lead to further efforts to grind POFA into higher fineness through the process of grinding and heat treatment. A better quality POFA known as ultrafine POFA has been produced, which further enhances the engineering properties and durability of concrete due to its

high pozzolanic reactivity and micro-filler effect [5]. Since then, research of ultrafine POFA has been gaining attention among the researchers and more studies need to be performed on ultrafine POFA so that knowledge on POFA can be well-established.

Alkali silica reaction (ASR) occurs due to the reaction between silica from the reactive aggregate and alkali from the cement, which leads to the formation of alkali silica gel [6]-[7]. In the presence of moisture, this gel will expand [8] and eventually causes concrete to crack [9]. Three factors affect ASR occurrence, which are reactive aggregates, high alkali cement and presence of moisture. In Sabah, most of the quarries are producing sandstone aggregates, which is considered as reactive [10]. This signifies that the aggregates are prone to the exposure of high alkaline solution. Higher alkalinity will increase the amount of hydroxyl ion ( $\text{OH}^-$ ), which is responsible for the dissolution of silica from the reactive aggregate [11]. Reaction of silica and the hydration product of cement will form alkali silica gel, which swells in the presence of moisture. To reduce the ASR, the main option is to use the non-reactive aggregate. However, since it is difficult to find non-reactive aggregate in some countries, another way is to replace parts of the cement with the pozzolan. Previous study revealed that POFA has the ability to suppress the ASR [12], but since the information is very limited, not much knowledge on the effect of ultrafine POFA on ASR is available. Realizing that, this paper aims to investigate the effects of ultrafine POFA on the alkali silica reaction of mortar bar.

## II. MATERIALS AND METHODS

### A. Materials Preparation

The materials used in this study were Ordinary Portland cement (OPC) Type I, palm oil fuel ash (POFA), coarse aggregates, granite, and river sand. Coarse aggregates were sandstone aggregates which were obtained from Penampang and Telipok quarries. The coarse aggregates were washed and open-dried for several days before it was crushed into various sizes according to ASTM C 1260 [13]. River sand was also dried and sieved to pass the 600  $\mu\text{m}$  sieve. The physical properties of aggregates are shown in Table I.

POFA used in this study was collected from Lumadan Palm Oil Mill in Sabah, Malaysia. The ashes were collected at the bottom of the tower shaft where it was trapped by a pond of water. The moisture content of the original POFA was 20% with specific gravity of 1.96. To remove the excess moisture, POFA was open-dried in lab condition for several days before it was placed in the oven at a temperature of 105  $^{\circ}\text{C}$  for 24h. To separate larger particles, POFA was sieved to pass 300  $\mu\text{m}$  (UG) and then kept in a sealed bag. To study the effect of ultrafine POFA on ASR, four types of particle sizes were used in this research, namely the unground (UG), medium (MP), fine (FP), and ultrafine size (UF). To reduce

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the size of POFA into MP, FP, and UF, two types of grinding equipment were used, which are the Los Angeles (LA) grinding machine and planetary grinding ball mill. Los Angeles abrasion machine was used to produce the ultrafine POFA. The stainless steel rods with 12 mm diameter and 450 mm length were used for grinding instead of using round steel ball mill due to its effectiveness in reducing the size of ashes [14] - [16]. 30,000 cycles of rotation were adopted to produce ultrafine size with 4 kg of POFA weighed for each batch of grinding. The samples were then ground in the planetary grinding mill for 30 minutes to improve its uniformity. Meanwhile, the medium (MP) and fine size POFA (FP) were produced through grinding of 600g of POFA for 1½ hour and 1 2/3 hour respectively, using the planetary ball mill grinding equipment. The physical and chemical properties of POFA and OPC are shown in Table II and Table III. Fig. 1 presents the SEM images for UG, MP, FP, and UF POFA.

Table I Physical Properties of Aggregates

Aggregates	Absorption (%)	Specific gravity <sub>app</sub>	Specific gravity <sub>app</sub>
Penampang	1.6	2.69	2684.95
Telipok	1.6	2.69	2,682.47
Granite	1.2	2.72	2710.76
River sand	11.0	2.67	2663.89

### B. Experiments

The ASR experimental program is divided into two stages; the first stage investigated the pessimum effect of the aggregates. In this stage, the amount of the test aggregates in the mixtures was assorted at 100%, 75%, 50%, 25%, 15%, and 5% by combining portions of the sandstone aggregates with granite. The ratio of cement to aggregate was 1:2.25 and water cement ratio was fixed at 0.47. The next stage was to select the portion of sandstone aggregates that exhibits the highest ASR expansion to be used in the final mixture. Incorporation of UG, MP, FP, and UF POFA was introduced at this stage with 10 – 40% replacing the cement. The performance of POFA to suppress the ASR was then evaluated.

The alkali silica reaction was measured based on the accelerated mortar bar test (AMBT) ASTM C 1260 [13] and ASTM C 1567 [17]. Three test specimens (25 mm x 25 mm x 280 mm) were cast for each mix group and covered with plastic sheet to prevent evaporation. After being left at room temperature for 24 h, the specimens were demoulded and initial comparator readings were taken. Afterwards, the specimens were fully immersed in water in closed plastic containers at 80°C for 24 h. After the period, the specimens were then removed from the container and an initial reading was taken to measure the zero point of the mortar bar length. To accelerate the ASR expansion, all specimens were submerged in the 1N NaOH at 80°C for 24 h. Measurements of the mortar bar length were done for every 4, 7, 11, 14, and 28 days of testing duration. Effect of POFA on ASR expansion was investigated by replacing 0 – 40% of cement with UG, MP, FP, and UF POFA. The expansion of mortar bars were evaluated based on the 14-day immersion in NaOH

solution. If the expansion is less than 0.1%, the aggregate is considered as non-reactive. An expansion that is higher than 0.2% is considered as highly reactive and between 0.1- 0.2%, the aggregate is considered as a slowly reactive aggregate [17].

For pozzolanicity test, the strength activity index test was adopted by mixing 250 g of OPC, 617.5 g of sand, and 121 g of water to produce control mortar. The test mixture was prepared by replacing 10 - 40% of the cement with UG, MP, FP, and UF POFA. The pozzolanic activity of POFA was determined based on the compressive strength of mortar with POFA replacing the cement [18]. The control mix and test mixtures samples were cast in 50 mm x 50 mm x 50 mm mould. After being demoulded, the cube samples were cured in saturated lime water and then tested for compressive strength at 3, 7, 28, and 56 days of testing. The strength activity index was calculated based on the average of the compressive strength of sample with POFA, and expressed as % of the compressive strength of control mix.

According to ASTM C311-04 [18], to cast mortars for strength activity index test, the quantity of water has to be adjusted to obtain flow of  $\pm 5$  of the control mix. Hence, the flowability tests were performed before commencement of the strength activity index test. A standard mould for flow test was used as recommended by ASTM C230/C230M [19]. After placing the mortar inside the mould, it was lifted and the flow table was dropped for 25 times in 15s. The mortar flow was then calculated based on the average of four diameter readings, and expressed as % of the original base diameter [20].

## III. RESULTS AND DISCUSSION

### A. Physical Properties and Morphology of POFA

The physical properties of POFA are presented in Table II. Grinding has reduced the size of POFA into finer materials with UF having average particle size of less than 2  $\mu\text{m}$ , FP and MP with average size of 3.0 and 39.5  $\mu\text{m}$ , respectively. Fig. 1 (a) – (d) show the morphology of POFA. It can be seen that UG has large and irregular-shaped particles with many pores on the surface. The microstructures of MP and FP become small, crushed and less irregular in shapes when it is ground to a finer size and fewer pores were observed on the particles. Further grinding of POFA has reduced the size into ultrafine (UF) size, with roughed irregular shaped finer particles. No pores were detected when it is in UF size. Reduction of the sizes has increased the specific gravity of POFA. Coarser POFA was characterized with porous particles and usually low in specific gravity [21]-[22]. By crushing the coarser POFA into finer particles, it reduced the porosity of the particles, hence the specific gravity increased. The same results were also found by other researchers when grinding POFA to a finer size [23]-[25]. On the other hand, reduction of size has increased the fineness of POFA. Fineness as measured using Blaine Permeability test shows that UF has higher fineness with a specific surface area of 839  $\text{m}^2/\text{kg}$ , while FP, MP, and UG with specific surface area of 570, 279, and 110  $\text{m}^2/\text{kg}$ , respectively.

Table II Physical Properties of Materials

Sample	Specific gravity	Blaine ( $\text{m}^2/\text{kg}$ )	D <sub>ave</sub> , ( $\mu\text{m}$ )
OPC	3.14	350	9.91

UG	2.04	110	119.9
MP	2.45	279	39.5
FP	2.50	570	3.0
UF	2.62	839	1.6

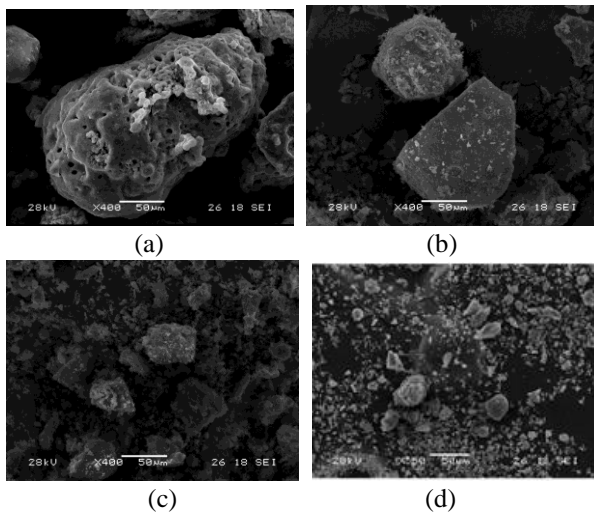


Figure 1 SEM Images of (a) UG, (b) MP, (c) FP and (d) UF POFA

### B. Chemical Composition of POFA

The chemical composition of POFA is shown in Table III. POFA has higher amount of  $\text{SiO}_2$  (45.40%) as compared to OPC (13.80%) but lower in  $\text{CaO}$  (6.02%) content. Higher silica content is one of the main characteristics of most pozzolan materials. Lower  $\text{CaO}$  indicates reduction in the strength of concrete or mortar when POFA is used in large amounts due to less formation of calcium silica hydrate (CSH) [26]. POFA used in this research can be classified as Class C pozzolan since the sum of the major oxide ( $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ ) is 50.31% [27]. This classification is similar with [28] although some of the researchers classified POFA as class N [29],[23] and F pozzolan [14]. Variation in the chemical composition of POFA was due to the difference in the burning temperature of the palm oil mills and material resources [30],[22]. The loss on ignition (LOI) of POFA used in this study is 4.96%, which indicates the presence of unburned residue due to improper burning of POFA [31]. Nevertheless, this value is still lower than the maximum value stipulated in the ASTM C618-03 (6.0%).

Table III Chemical Properties of OPC and POFA

Chemical composition %	OPC (%)	POFA (%)
Silicon dioxide, $\text{SiO}_2$	13.80	45.40
Aluminium Oxide, $\text{Al}_2\text{O}_3$	3.34	2.09
Iron oxide, $\text{Fe}_2\text{O}_3$	3.83	2.82
Calcium Oxide, $\text{CaO}$	56.89	6.02
Magnesium oxide, $\text{MgO}$	1.88	4.84
Sodium oxide, $\text{Na}_2\text{O}$	0.13	0.11
Potassium oxide, $\text{K}_2\text{O}$	1.08	7.07
Sulphur trioxide, $\text{SO}_3$	3.51	0.19
$\text{P}_2\text{O}_5$	0.04	4.97
LOI	0.41	4.96
S + A + F	N/A	50.31

### C. Effect of POFA on Flowability of Mortar

The difference between the effect of UG, MP, FP and UF on mortar flow and water requirement is presented in Table IV and Fig. 2. In this experiment, water content of the POFA mixtures was adjusted to get  $\pm 5$  of the control flow. Results

show that the mortar flow decreased with the increase in size and level of replacement of POFA. At 10% of POFA replacement, UG mortar shows higher water requirement with 109%. As the amount of replacement increased, more water is required to lubricate the mix. UG40 shows 24% increment in water requirement to obtain a flow of 105%. This indicates that coarser POFA tends to increase the amount of water required in the mix. MP POFA exhibits the same reduction effect on the mortar flow spread, but the amount of water required to obtain the constant flow is slightly less compared to UG. However, the effect was only seen with the amount of replacement from 20 – 40%. No reduction on the mortar flow was observed for MP10. Instead of fineness, the flowability of coarse POFA was also affected by the amount of POFA replacement. Both mixes show increment in water requirement as the amount of POFA replacement increased. Increase in water demand of UG and MP POFA is largely due to the fact that POFA has irregular shape and is a porous material. Crushed shape and high porosity lead to more water being absorbed in the particles. For MP POFA, less porous particles were produced due to the grinding effect. Hence, the amount of water required to obtain the standard flow was also decreased as compared to UG POFA. The absorption caused insufficient water to lubricate the mix; therefore the mix is less workable.

In contrast, the fine (FP) and ultrafine size (UF) have resulted in significant improvement on the mortar flow without the addition of extra water to fluidify the mix. At the same amount of water (w/c 0.48), FP shows mortar flows between 105 - 114%, while UF with flow of 115, 115, 110, and 111%, for UF10, UF20, UF30, and UF40, respectively. Even though UF10 demonstrated 98% reduction in water requirement, the flow is still higher (115%) than the control mortar (110%). This reveals that grinding has significantly improved the properties of POFA produced. With reduction on the porosity, less water is absorbed in the particles; hence more water is available to fluidify the mixes. Ultrafine POFA was observed to give high paste volume to the mixes, which helps in improving the lubrication of the mix, so a good flow of mortar is obtained [24].

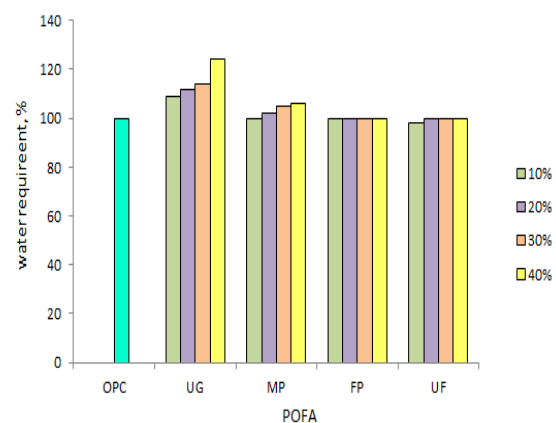


Figure 2 Water requirement of mortar with various POFA replacements

Table IV. Flow and Water Requirement of POFA Mortar

Sample	Flow (%)	Water requirement (%)
CM	110	100
UG10	111	109
UG20	113	112



UG30	105	114
UG40	105	124
MP10	100	100
MP20	107	102
MP30	115	105
MP40	105	106
FP10	111	100
FP20	114	100
FP30	105	100
FP40	106	100
UF10	115	98
UF20	115	100
UF30	110	100
UF40	111	100

#### D. Pozzolanic Reactivity of Mortar

ASTM C-618 has set a standard for a material to be accepted as pozzolan, where it should meet the 75% limit at 7 and 28-day strength. In this research, the pozzolanic reactivity of ultrafine POFA was evaluated through the strength activity index of mortars with POFA replacement at 10, 20, 30, and 40% and tested at 3, 7, 28, and 56 days. The result of strength activity index is presented in Fig. 3. At the early strength of mortars, only 10% of POFA replacement regardless of their sizes has shown higher strength activity index compared to the control mortar, CM. Increasing the level of POFA replacement has reduced the strength of activity index. It has been reported that the pozzolanic reactivity of POFA is slower at the early stage of hydration [32]. At early age of mortar, the higher the amount of POFA replacement, the slower the pozzolanic reactivity of the mortar. As the age of mortar increases, the pozzolanic reactivity of POFA mortars increased significantly. At 28-day, all types of POFA with replacement of 10 - 40% exceed 75% of the CM strength and at 56-day testing, UF1, UF2, UF3, and UF4 exhibit strength activity index higher than CM with 112, 114, 99 and 97%, respectively. It was also found that at later age (56-d), UF2 and FP2 (20% replacement) show the highest pozzolanic reaction compared to all level of POFA replacements.

Ultrafine POFA was seen to give higher pozzolanic reactivity at all ages of testing compared to other types of POFA. FP also shows good pozzolanic reactivity due to its finer size. UG and MP POFA exhibit the slower pozzolanic reactivity among the four types of POFA. This might be due to the coarser size compared to UF and FP. Coarse POFA has low specific surface area which causes slow pozzolanic reaction. From Fig. 3, it is clear that the fineness of POFA plays an important role in increasing the pozzolanic reactivity of POFA. The higher the fineness of POFA, the greater was the pozzolanic reaction and rate of hydration of the samples [36]. High pozzolanic reaction will increase the reaction of silica with  $\text{Ca}(\text{OH})_2$  from the cement to produce extra CSH, which contribute to the strength development of mortar [33]-[34]. The same behavior was also reported by [22] and [35]. Furthermore, high fineness POFA was able to act as microfiller, which fills voids between the cement and sand, therefore the mortar becomes denser and the compressive strength increases [21].

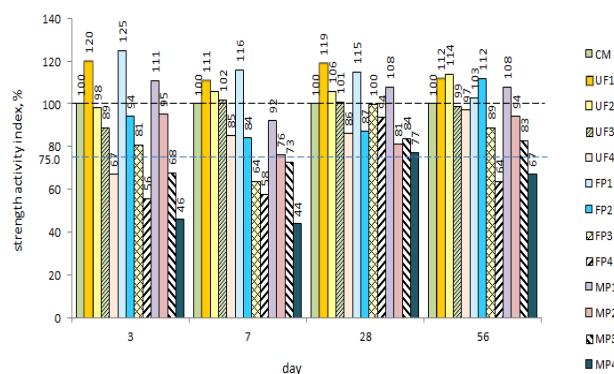


Figure 3 Pozzolanic Reactivity of Mortar Containing POFA

#### E. Alkali Silica Reaction (ASR)

##### Pessimum Effect of Aggregates

The pessimum effect of sandstone aggregates from Penampang and Telipok quarries was investigated by blending 100%, 75%, 50%, 25%, 15%, and 5% of sandstone aggregates with granite. The effect of the replacements on ASR expansion is shown in Fig. 4 (a) and (b). During the earlier immersion of mortar bar, the expansion of 75% aggregates was slightly higher than the expansion of 100% aggregates. For example, the expansion of 75P was 1.5% higher (0.134%) than the expansion of 100P (0.132%) at day 7. The same results were also observed for Telipok aggregates with expansion of 0.080% and 0.074% for 75T and 100T, respectively. This temporary pessimum effect exists due to a difference in the rate of attack of the hydroxyl ions with reactive silica in aggregates. Larger amount and size of aggregate usually cause slow penetration of ions to react with the silica. More time is needed for the  $\text{OH}^-$  to penetrate the aggregates, therefore causing delay for 100% aggregate specimen to reach maximum expansion at earlier age of testing [37]. However, at day 14, both 100P and 100T samples show highest ASR expansion with 0.263% and 0.294%, respectively.

Expansion of more than 0.2% at day 14 indicates that both Penampang and Telipok aggregates are considered as highly reactive aggregates. This is followed by 75%, 50%, and 25% mortar specimens with expansion of 0.241, 0.236, and 0.223% for Penampang aggregate, while 0.208, 0.186, and 0.126% for Telipok aggregate, respectively. However, the mortar bars containing 5% of sandstone aggregate (5P and 5T) somehow exhibit higher expansion than 15P and 50T specimens. The size of granite used as reactive aggregate replacement was randomly mixed between 600  $\mu\text{m}$  - 2.36 mm. Since it is not controlled, the finer size of granite particle might be present in large amounts in the mortar bar samples. According to [37], the larger the aggregate particles, the slower the expansion rate of mortar due to ASR. Therefore, higher amount of finer aggregate particle might increase the rate of  $\text{OH}^-$  reaction with silica from aggregate; thus high expansion can be seen in 5T and 5P mortar bar specimens. Nevertheless, the amount of expansion is still lower than the 100% samples due to lower amount of reactive aggregates in 5T and 5P mortar specimens. Meanwhile, the granite aggregate shows expansion between 0.1% and 0.2% (0.189%), which is considered as slowly reactive aggregate. Based on the results, there is no pessimum effect of sandstone

aggregates on ASR. The amount of reactive aggregates might be the main parameter affecting the degree of damage since all specimens containing 100% aggregates show highest expansion at day 14.

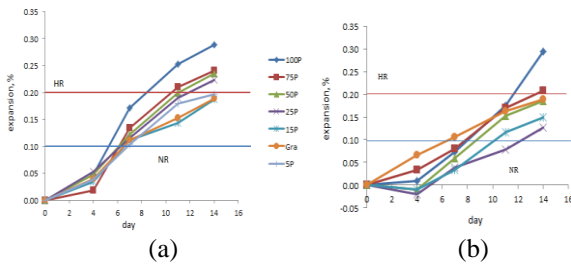


Figure 4 Pessimistic ASR Expansion of Mortar Bar Containing (a) Penampang Aggregate (b) Telipok Aggregate (NR-Non-reactive, HR-Highly reactive)

#### Effect of POFA on the Alkali Silica Reaction

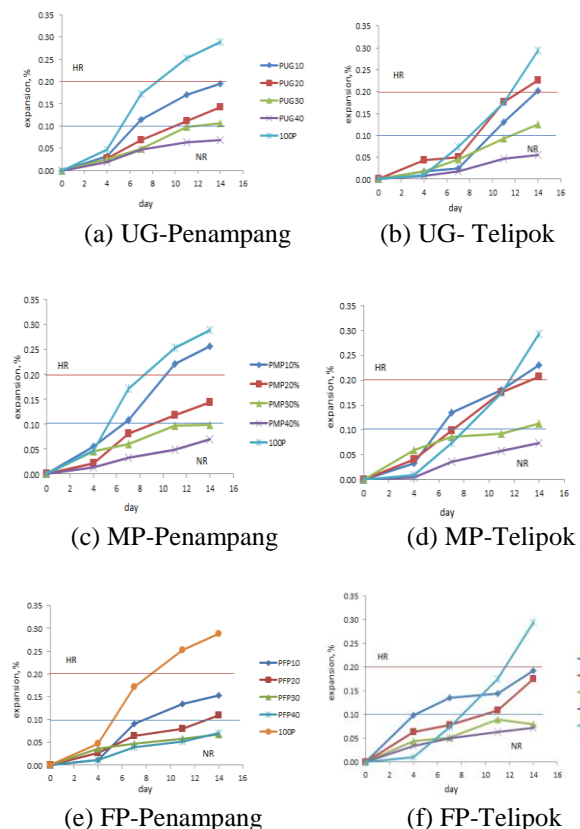
The effect of POFA fineness on ASR is presented in Fig. 5 (a) – (h). The results of mortar bars expansion containing POFA was interpreted according to ASTM C1567. Expansion of more than 0.20% indicates mortar bar with highly reactive behavior, between 0.1 - 0.2 as slowly reactive and less than 0.1% as non-reactive behavior. Based on Fig. 5(a) and 5(b), UG POFA was unable to suppress the ASR of Penampang and Telipok aggregates, particularly for the replacement level up to 30%. Even though the expansions are lower than the control mortar bar, it is still unable to reduce the expansion below the lower limit of 0.1%.

The same trend was also observed for MP specimens (Fig. 5(c) and 5(d)). MP mortar bar demonstrates expansion that is slightly lower than the UG specimens, especially when the level of replacement increased up to 30%. However, the amount of reduction is not enough to prevent the ASR damage. Nevertheless, 40% of cement replacement for both UG and MP POFA shows reduction of expansion below 0.1%. PUG40 and TUG40 show the lowest expansion with 0.069 and 0.093%, while PMP40 and TMP40 with 0.070 and 0.033%, respectively. Awal et al. [12] showed similar findings when 30% of POFA replacement failed to reduce the expansion of mortar bar due to ASR. However, the author used different intervals of cement replacement, which demonstrates 50% as the optimum amount of POFA suppressing the ASR. The results of our study revealed that the optimum amount for coarser POFA to suppress the ASR is 40%.

Grinding of POFA into finer size has improved its ability to suppress ASR. With 30% of cement replacement, FP POFA was able to reduce the expansion below 0.1% in comparison to UG and MP samples (Fig. 5(e) and 5(f)). Reduction of POFA to ultrafine size has demonstrated a remarkable improvement on the mortar bar expansion. With only 20% of cement replacement, both TUF20 and PUF20 suppress the ASR at 14 days with expansion of 0.098 and 0.042%, respectively, which is lower than 0.1% (Fig. 5 (g) and (h)). 10% replacement was unable to suppress the ASR expansion in mortar bar. These results suggest that the higher the fineness of the POFA, the better is its ability to reduce the ASR expansion. As discussed in previous section, high fineness of POFA will contribute to the improvement of the pozzolanic reactivity of the POFA mortar. Due to higher pozzolanic reaction, more CSH is produced in the pastes

[38]. The CSH will occupy large voids within the pastes to make it denser. High pozzolanicity also cause depletion of alkalis, hence the ASR expansion is reduced [39]. Depletion of alkalis will reduce the  $\text{OH}^-$  released in the pores which lead to less silica dissolution within the mortar. On the other hand, high fineness of ultrafine POFA can act as microfiller, which refines the pore structures within the paste [40]. A highly impermeable matrix is formed within the mortar bar [21] to prevent the penetration of alkali solution into mortar bar, therefore the expansion is reduced.

In contrast, coarser POFA (UG and MP) causes slow pozzolanic reaction between silica and  $\text{Ca}(\text{OH})_2$ . Not much CSH is produced to form dense structures within the mortar. Hence, they are unable to prevent ASR expansion at lower rate of cement replacement compared to UF POFA due to low pozzolanic effect. Nevertheless, at 40% of cement replacement, coarser POFA was able to suppress the ASR. This might be due to high POFA/cement ratio that will lead to the dilution effect [33],[41]. Replacement of cement with high amount of POFA has reduced the alkalinity ( $\text{OH}^-$ ) of the pore solution within the mortar bar; hence it reduces the dissolution of the silica from the reactive aggregate. Reduction of the silica dissolves in the pore solution led to less formation of the alkali silica gel. Thus, expansion observed on the mortar bars with high POFA/cement ratio (40%) was found to be lower than 0.1% (non-reactive). The shrinking effect observed on TUF40 and PUF40 might be due to autogenous shrinkage [42]. The coupling effect of high pozzolanic effect and dilution effect of POFA have caused formation of dense structure of mortar bar. This has delayed the expansion reaction due to slow penetration of alkaline solution into mortar bar.



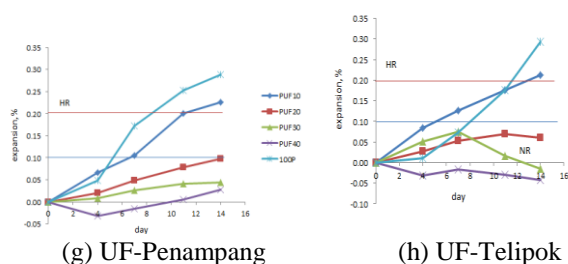


Figure 5 (a) – (h) Effect of POFA Fineness on the ASR of Mortar Bar (NR-Non-reactive, HR-Highly reactive)

#### IV. CONCLUSIONS

The results of this study suggest that the efficiency of POFA to suppress the ASR depends on the fineness and level of replacement.

- 1) Increasing the fineness of POFA has improved its efficiency to reduce the ASR. Higher fineness of ultrafine POFA allows suppression of the ASR expansion at lower level of cement replacement (20%). The ultrafine POFA improves the pozzolanic reaction through the formation of extra CSH, which fills the void within the paste to produce a dense and impermeable microstructure mortar. At high POFA/cement ratio, the dilution effect together with the pozzolanic effect has caused delay on the ASR expansion due to slow penetration of alkaline solution into mortar bar.
- 2) Coarser POFA is unable to suppress the ASR at low POFA replacement level due to having low pozzolanic reactivity. However, at high POFA/cement ratio particularly at 40% POFA replacement, the dilution effect has improved the ability of POFA to suppress the ASR. Reduction of the alkalinity of pore solution lead to less formation of the alkali silica gel, hence ASR expansion in mortar bar is reduced to a value lower than 0.1%, which is considered as non-reactive.
- 3) Higher fineness of POFA improves the pozzolanic reactivity of POFA particularly at later ages. At 7 and 28-day, UF POFA with 10 - 30% replacements shows higher pozzolanic reactivity than the control mortar, whereas 40% UF shows 85% of strength activity index. This suggests that by reducing the size of POFA into ultrafine size, not only it improves the ASR resistance of mortar when used at low level of replacement (20%) but it also improves the pozzolanic reactivity and compressive strength at higher level of replacement. Hence, the use of POFA in construction not only will resolve the POFA disposal problem, but it also solves the ASR durability problem particularly in countries which reactive aggregates become their main sources.

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